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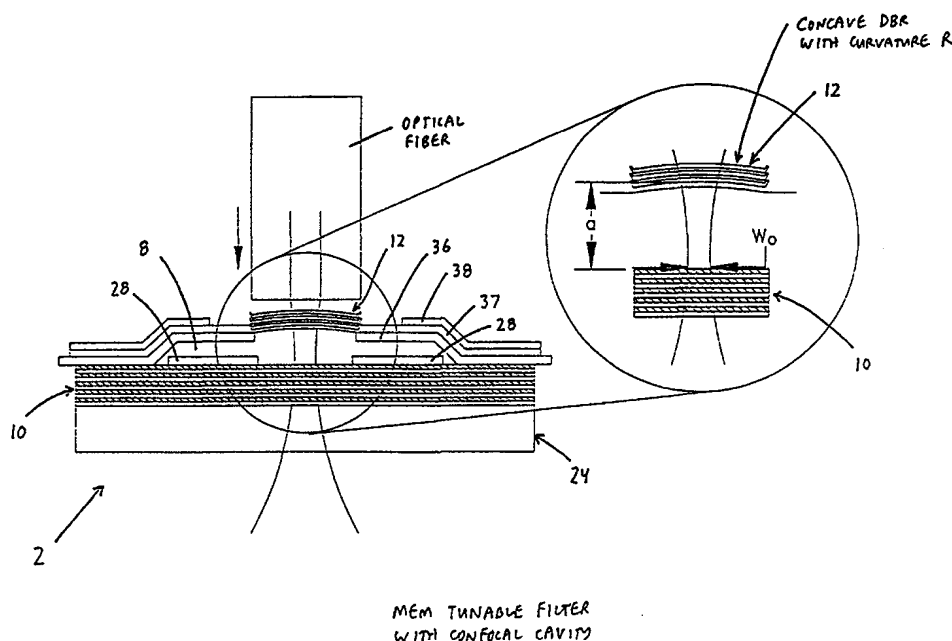
(54) Title: MICROELECTROMECHANICALLY TUNABLE, CONFOCAL, VERTICAL CAVITY SURFACE EMITTING LASER AND FABRY–PEROT FILTER

(57) Abstract

A method is provided for fabricating microelectromechanically tunable vertical–cavity surface–emitting lasers and microelectromechanically tunable Fabry–Perot filters with precise lateral and vertical dimensional control. Strained reflective dielectric film(s) are applied to a multiple quantum well structure to electronically band–gap–engineer the quantum wells. Appropriate strain in the reflective dielectric film layers is also used to create appropriate curvature in one of the reflective dielectric film stacks so as to form a confocal cavity between a planar reflective dielectric film layer and the curved reflective dielectric film layer in the vertical cavity surface emitting laser or filter. Microelectromechanical tunable vertical cavity surface emitting lasers and filter structures are also provided which include a suspended membrane structure made of a dielectric/metal membrane or metal film that supports a cavity–tuning reflective dielectric film stack while being anchored at the perimeter by metal support post(s). Precise air–cavity length and lateral dimensions are achieved by micro–die–casting using a micro–machined sacrificial polyimide or aluminum disk. Further, tuning is achieved by translational movement of the cavity–tuning reflective dielectric film stack in a controlled electrostatic field.

MEM TUNABLE FILTER WITH CONFOCAL CAVITY

MICROELECTROMECHANICALLY TUNABLE,

CONFOCAL, VERTICAL CAVITY SURFACE EMITTING

LASER AND FABRY-PEROT FILTER

Reference To Pending Prior Provisional Patent Application

This patent application claims benefit of pending prior U.S. Provisional Patent Application Serial No. 60/068,931 filed 12/29/97 for MICROELECTROMECHANICALLY TUNABLE CONFOCAL VERTICAL CAVITY SURFACE EMITTING LASER VCSEL AND FABRY PEROT FILTER.

Field Of The Invention

The present invention relates to semiconductor optoelectronic devices in general and, more particularly, to wavelength tunable surface emitting semiconductor lasers and filters.

Background Of The Invention

Tunable vertical cavity surface emitting lasers (VCSEL's) and filters have recently generated considerable interest in the art. This is because these devices show great promise not only for

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increasing bandwidth during wavelength division

multiplexing (WDM) in fiber-optic communications, but

also for use in switches, routers, highly compact

spectroscopic interferometers, optical trans-receivers

and numerous other applications.

More particularly, VCSEL's are extremely

attractive for integrated optoelectronic circuits. For

one thing, they operate at a single longitudinal mode

with a circular aperture, thereby providing efficient

coupling to fibers. In addition, they are compact, and

can be monolithically fabricated in large, dense arrays

on a wafer-scale.

As a fixed wavelength light source, VCSEL's have

demonstrated limited application and functionality.

Some past effort has been directed towards

achieving wavelength tuning in VCSEL's by introducing

refractive index changes with (1) temperature (see, for

example, Berger, P. R., Dutta, N. K., Choquette, K. D.,

Hasnain, G., and Chand, N., "Monolithically

Peltier-cooled vertical-cavity surface-emitting

lasers", Applied Physics Letters, Vol. 59, No. 1, pp.

117-119, 1991; and Chang-Hasnain, C. J., Harbison, J.

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P., Zah, C. E., Florez, L. T., and Andreadakis, N. C.,
"Continuous wavelength tuning of two-electrode vertical
cavity surface emitting lasers", Electron. Lett., Vol.
27, No. 11, pp. 1002-1003, 1991); or (2) carrier
injection (see, for example, Gmachi, C., Kock, A.,
Rosenberger, M., Gornik, E., Micovic, M., and Walker,
J. F., "Frequency tuning of a double-heterojunction
AlGaAs/GaAs-vertical-cavity surface-emitting laser by a
serial integrated in-cavity modulator diode", Applied
Physics Letters, Vol. 62, No. 3, pp. 219-221, 1993).

Both of these techniques provide a tuning range of
roughly 10 nm; however, this is still considerably
short of the several tens of nanometer tuning range
which is necessary for bandwidth-hungry WDM and dense
WDM applications.

In contrast, variation of the length of a
Fabry-Perot cavity has been shown to be a viable
technique for accomplishing wavelength tuning in
VCSEL's without affecting the laser gain medium.
This can be achieved in surface emitting devices by the
provision of a top mirror that can be translated
relative to the bottom mirror by the application of an

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electrostatic field. This technique has been

implemented in tunable Fabry-Perot devices such as

(1) filters (see, for example, Larson, M. C., Pezeshki,

B., and Harris, J. S., "Vertical coupled-cavity

microinterferometer on GaAs with deformable-membrane

top mirror", IEEE Photonics Technology Letters, Vol. 7,

pp. 382-384, 1995; and Tran, A. T. T. T., Lo, Y. H.,

Zhu, Z. H., Haronian, D., and Mozdy, E., "Surface

Micromachined Fabry-Perot Tunable Filter", IEEE

Photonics Technology Letters, Vol. 8, No. 3,

pp. 393-395, 1996); (2) light emitting diodes (see, for

example, Larson, M. C., and Harris, J. S.,

"Broadly-tunable resonant-cavity light emission",

Applied Physics Letters, Vol. 67, No. 5, pp. 590-592,

1995); and (3) VCSEL's (see, for example, Wu, M. S.,

Vail, E. E., Li, G. S., Yuen, W., and Chang-Hasnain, C.

J., "Tunable micromachined vertical-cavity surface

emitting laser", Electronic Letters, Vol. 31, No. 4,

pp. 1671-1672, 1995; and Larson, M. C., Massengale, A.

R., and Harris, J. S., "Continuously tunable

micromachined vertical-cavity surface emitting laser

with 18 nm wavelength range", Electronic Letters,

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Vol. 32, No. 19, pp. 330-332, 1996).

In devices of this sort, the amount of deflection of the top mirror depends on a number of parameters, e.g., the length, width, thickness and Young's modulus of the mirror-supporting arm. Although the aforementioned width, thickness and Young's modulus of the mirror-supporting arm are generally fairly precisely controllable, the current fabrication techniques used in such devices generally provide very limited control over the exact length of the supporting arms. This results in significant performance variations from device-to-device and batch-to-batch.

The present invention provides the precise dimensional control necessary for realizing reproducible, tunable Fabry-Perot devices that are necessary for producing commercially usable tunable filters and VCSEL's.

Some Aspects Of The Present Invention

This patent application claims benefit of pending prior U.S. Provisional Patent Application Serial No. 60/068,931 filed 12/29/97 for MICROELECTROMECHANICALLY

TUNABLE CONFOCAL VERTICAL CAVITY SURFACE EMITTING LASER

VCSEL AND FABRY PEROT FILTER, which document is hereby

incorporated herein by reference.

The present invention comprises a novel,

microelectromechanically (MEM) tunable, confocal

filter.

The present invention also comprises a novel, MEM

tunable, confocal vertical cavity surface emitting

laser (VCSEL).

The laser preferably utilizes post-growth control

of strain in the quantum wells.

In addition, the present invention also comprises

a novel technique for VCSEL/filter fabrication which

provides the precise dimensional control necessary for

mass producing reliable devices having predictable

performance characteristics.

More particularly, the present invention provides

a new technique for introducing appropriate strain into

a thin, lattice-matched layer of laser active medium,

i.e., in the quantum wells, after crystal growth has

been effected. This is achieved by depositing

distributed Bragg reflectors (DBR's) on the laser

active medium, wherein the distributed Bragg reflectors comprise carefully engineered, strained, dielectric multi-layer films. By carefully modifying the strain in the deposited DBR films, the strain and the gain properties of the quantum well regions can be optimized. In VCSEL's, when quantum wells are under compressive strain, the differential gain of the laser increases, and threshold current density decreases, thereby dramatically improving the performance of the VCSEL's. Tensile strain, on the other hand, has adverse effects on the lasing properties of VCSEL's. Dielectric multi-layer combinations, such as silicon (Si) and aluminum-oxide (Al_2O_3), or Si and silicon-dioxide (SiO_2), or Si and magnesium-oxide (MgO), or TiO_2 and SiO_2, can be deposited by means of ion-beam assisted electron-beam evaporation or ion-beam assisted ion-beam sputtering, with a controlled strain in the deposited films. By carefully controlling the ion-beam voltage and current, dielectric films with either tensile or compressive strain can be deposited, with the magnitude of the strain ranging from a few Kilo Pascal (KPa) to a few Giga Pascal (Gpa). These

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multi-layer dielectric films provide a multi-purpose

function, i.e., they induce strain in the quantum

wells, they provide optical feedback to the gain

medium, and they efficiently remove heat from the

active region, all of which are important aspects of

creating commercially useful VCSEL's, especially in the

wavelength range of between about 1300 nm and about

1500 nm.

The present invention also includes another

innovation for producing, via micromachining, a

confocal cavity VCSEL that comprises a tunable cavity

formed between a set of planar DBR's and a set of

curved DBR's. Curvature in the DBR's is achieved by

the judicious introduction of an appropriate magnitude

of strain in the deposited layers. By the creation of

a confocal microcavity, the spatial mode and divergence

of the laser mode can be controlled precisely so as to

(a) produce single spatial modes by optically

restricting the lasing domain in the gain region, and

(b) manipulate the divergence angle of the VCSEL so as

to optimize the coupling of generated light into a

single mode fiber.

The fabrication techniques of the present invention provide extremely precise control of the physical dimensions of both the top DBR structure and the supporting structure, which is indispensable for achieving highly reproducible performance with inconsequential device-to-device variation.

Another aspect of the present invention is a confocal microelectromechanical tunable Fabry-Perot structure. When the gain region is left out of the foregoing confocal VCSEL structure, only the optical cavity remains, and the device acts as a confocal Fabry-Perot filter. The confocal nature of the short cavity (e.g., 0.2-10 micron) device allows efficient coupling of light (i) from an input single mode fiber to the device, and (ii) back out to a single mode output fiber.

Confocal tunable filter and VCSEL devices are depicted in Figs. 1 and 2, respectively. These devices operate at a single longitudinal mode over the entire bandwidth (e.g., 30-120 nm) of the gain medium, in the case of a VCSEL; and over a 100 nm tuning range, in the case of a filter.

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As depicted in Fig. 1, the tunable Fabry-Perot filter device comprises (i) a distributed Bragg reflector (DBR) with a curvature R, formed by high index contrast multi-layers atop a thin membrane (or tethers) of silicon nitride (Si_3N_4) or a thin metal film such as titanium-tungsten (TiW), wherein the membrane is supported at its perimeter by thicker metal posts, (ii) an air cavity formed by selective removal of a sacrificial layer, and (iii) a bottom set of dielectric DBR's deposited in the substrate facing the top DBR.

In the case of a VCSEL, a gain medium, consisting of multiple quantum wells, is inserted in the air cavity as shown in Fig. 2. These VCSEL's can be photo-pumped, or intra-cavity electrical interconnections can be made for current injection.

Of course, it is also to be appreciated that the tunable filter, and/or the tunable VCSEL, can be formed with a top distributed Bragg reflector having a planar configuration, without departing from the scope of the present invention.

The following is a list of some technological

breakthroughs resulting from the present invention.

Strain-Optimized Fixed-Wavelength VCSEL's

Since, in a VCSEL, the resonant optical mode interacts with an extremely small volume of gain medium, it is imperative that the gain medium provide maximum differential gain, while the DBR's provide maximum feedback and the least thermal resistance possible.

Although using compressively strained multiple quantum wells can provide the maximum possible gain, there is a limitation on the maximum number of strained quantum wells that can be grown without generating crystalline defects.

A solution to this problem is to grow strain-compensated multiple quantum wells. In practice, however, this is difficult and costly. Although GaAs/GaAlAs-based VCSEL's show maturity, the presently preferred material system for long wavelength (e.g., 1300 nm and 1500 nm) lasers is InP/InGaAsP-based, and much improvement upon this material system remains to be made.

Since the maximum index contrast between InP and InGaAsP is only about 0.2, a large number of quarter-wave stacks are required in order to provide sufficient feedback. This, however, causes significant resistive losses in the device, and an unacceptable degree of thermal bottleneck. In addition, the low index-contrast also results in relatively narrow bandwidth mirrors, thereby placing a severe constraint on the accuracy of the mirror thickness.

The present device may consist of an InGaAsP/InGaAs multiple quantum well (MQW), with a dielectric DBR on top and a dielectric DBR between the MQW and the substrate. See, for example, Fig. 5, which illustrates a fixed wavelength VCSEL. If desired, the fixed wavelength VCSEL may have a curved top distributed Braff reflector. Both DBR's are deposited by vacuum deposition techniques.

As summarized below, the present invention provides a solution to all of the foregoing problems, simultaneously, with implications of significant cost reduction and high manufacturing yield.

1.   Deposited DBR's can externally alter the

strain in the quantum well regions of the MQW, thereby
modifying the gain coefficient, threshold current and
slope-efficiency. By controlling the strain of the
deposited DBR, the strain in the quantum wells, and
therefore the lasing properties of the VCSEL, can be
optimized. Post crystal-growth modification of strain
in the quantum wells relieves the constraint of
devising expensive and difficult strain-compensation
techniques employed in epitaxial crystal growth (MBE or
MOCVD).

     2.   In epitaxially grown monolithic VCSEL's,
thickness variations across the wafer cause lasing
wavelength variations, resulting in poor yield. Since
the index contrast between Si and Al_2O_3 is relatively
high (i.e., about 2.8), with only four pairs of DBR's,
over 99.9% reflectivity can be achieved over a large
bandwidth (e.g., 500 nm). As a result, a Fabry-Perot
cavity formed by these DBR's creates a high-Q cavity
with sufficient feedback. Since the mirrors are broad
band, the stopgap of the mirror can easily straddle
over 100 nm of the gain spectrum. Any thickness
variations in the active layer, and/or in the cladding

thickness over the wafer, can be compensated for by
depositing phase-compensating layers of dielectric
films before depositing the final DBR mirror. This
allows harvesting most of the wafer for the desired
wavelength of emission. The high reflectivity of the
DBR mirrors also helps to lower threshold conditions.

      3. Dielectric mirrors formed by materials
such as Si and Al_2O_3 or MgO have a very high thermal
conductivity, thereby providing for efficient removal
of heat from the active region. In addition, only a
few pairs of DBR's are required; hence, the thermal
path to the heat sink is shorter in the present
invention than in traditional semiconductor DBR's,
thereby adding to the efficient heat removal process.

<u>Wavelength Tunable VCSEL's</u>

    A schematic diagram of the steps used in
fabricating a novel wavelength tunable VCSEL based on
the present invention is shown in Fig. 4. The device
comprises bottom DBR's consisting of
high index-contrast dielectric pairs such as Si/Al_2O_3,
Si/SiO_2, Si/MgO, or TiO_2/SiO_2, along with

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selectively-deposited top DBR mirrors, with an
air-cavity and an active medium embedded in the
Fabry-Perot cavity formed by the two DBR's.

The present invention also accommodates a hybrid
mirror system such as bottom epitaxially grown DBR's
and top deposited DBR's.

The top DBR resides on a thin, supporting membrane
or multiple tether structure made of Si_3N_4 or metal
(TiW) that is supported at its perimeter by a thicker
metal support (see Figs. 6A-6C). This forms a
trampoline type of structure. In the case of a
circular membrane structure, radially extending
openings in the Si_3N_4 or metal film (TiW) are used for
selectively removing an underlying sacrificial layer
during the top DBR release process, as will be
discussed further below.

By applying an appropriate voltage across this
membrane and the bottom DBR's, the trampoline
structure, along with the top mirror, can be translated
toward, and away from, the bottom DBR so as to tune the
laser emission. Since the DBR's are broad band, tuning
is possible over the entire bandwidth of the laser gain

spectrum, which is nominally about 60 nm.

One of the important features of the present
invention is that the new fabrication process provides
precise control over the lateral dimensions of the
trampoline structure and the air-cavity length, both of
which are important for the consistent manufacturing of
substantially identical devices. This is made possible
in the present invention by allowing the sacrificial
layer to act as a die in order to define the lateral
dimensions of the trampoline structure and the vertical
dimension of the air-cavity. As a result, the possible
ill effects of uncontrolled dimensions, ensuing during
the selective removal of the sacrificial layer, are
effectively eliminated.

In addition, the new devices are small and compact
(approximately 500 μm × 500 μm), thereby allowing
arrays thereof to be manufactured and coupled to
fibers.

Wavelength Tunable Filter

As shown in Fig. 3, the tunable Fabry-Perot filter
is obtained by omitting the quantum well gain material

from the above-described VCSEL structure.

High index-contrast DBR stacks provide broad bandwidth (e.g., 500 nm); hence, for a lambda-cavity, the Fabry-Perot resonance can be tuned over the entire bandwidth of the DBR's. Since the reflectivity of the DBR's is high, an extremely narrow (sub-Angstrom) linewidth is attainable.

Tuning speed in these devices is on the order of microseconds, making them one of the fastest tunable filters, with extremely high spectral resolution. These devices are also easily mass-produced using standard semiconductor fabrication techniques, thereby making them affordable for consumer products.

Tunable VCSEL/Filter With Confocal Cavity

The MEM tunable Fabry-Perot filter with confocal cavity is a highly innovative resonator design that comprises an air cavity between a first set of distributed Bragg reflectors (DBR's) that are planar and a second set of DBR's having a finite radius of curvature. These two sets of DBR's form a confocal cavity as shown in Fig. 1.

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One innovation of this design is the fact that the
curvature of one of the mirrors creates a
micro-resonator that can sustain Hermite Gaussian
modes. As described below, by introduction of
appropriate curvature in the top mirror, coupling of
light from a standard single mode fiber into and out of
the device can be simplified by avoiding the use of
lenses that are otherwise necessary.

It is well known that the Rayleigh range, z_0,
which defines the distance at which the wave front is
most curved, is related to mirror curvature, R, and
cavity length, d, by the equation $z_0 = [(R-d)/d]^{1/2}$
("Equation 1"). For instance, a resonator with a
cavity length of 1.5 microns, and a radius of curvature
of 1.5 millimeter for the curved DBR's, leads to a z_0
value of 150 microns, and to a fundamental mode beam
waist, W_0, of 8.5 microns at a wavelength, λ, of 1.5
microns, according to the relationship
$W_0 = (z_0\lambda/\pi)^{1/2}$ ("Equation 2"). Since the value of the
mode size at position z is given by the equation
$W(z) = W_0[1+(z/z_0)^2]^{1/2}$ ("Equation 3"), and since z_0 is
approximately a hundred times larger than the cavity

length, the mode size remains virtually the same over
the length of the cavity. Consequently, light from a
9-micron-core, single-mode fiber on the input side can
excite this fundamental mode, and the transmitted
single mode beam can be efficiently coupled to a
single-mode fiber. As such, by curving the mirror, the
mode spot size can be adjusted to match that of a
single mode fiber without requiring a lens. The trade
off is, however, that in this case the fiber has to be
positioned within 0.5 micron (in the lateral direction)
with respect to the optical axis of the cavity in order
to avoid exciting undesirable higher order Hermite-
Gaussian modes. In order to improve the alignment
tolerance of the coupling fiber, a thermally expanded
core fiber with mode size of 20-50 microns can be used
in conjunction with mirrors with appropriately reduced
curvature. The curvature R of the mirror is adjusted
based on Equations 1-3 above to match the mode size W_o
of the thermally expanded core fiber. Because of the
larger size of the Gaussian mode, the lateral
positioning of the fiber is relaxed.

This design is distinctly different from the

single-crystal, parallel mirror resonator design

disclosed in U.S. Patent No. 4,825,262, issued

April 25, 1989 to Stephen R. Mallinson.

The processing steps for the fabrication of a

novel MEM tunable filter with a confocal cavity of the

present invention are similar to those utilized in the

fabrication of a novel planar cavity tunable

filter/VCSEL of the present invention. A

significant difference is in the deposition of the

curved DBR's. Control of the magnitude and type of

strain in the deposited multilayer dielectric stack of

DBR's, and the supporting thin silicon-nitride

membrane, is carefully engineered so as to achieve the

desired mirror curvature. The magnitude and the type

of strain (tensile or compressive) is introduced in

these films by the judicious choice of deposition

parameters, such as the ratio of the gas mixtures of

silane (SiH_4) and ammonia (NH_4), the total pressure of

the gases used, and the magnitude of RF power used.

The resulting stress gradient between the tensile

strain silicon-nitride membrane and the compressively

strained dielectric mirror stacks results in a concave

DBR. Further control of the curvature of the top DBR
can be achieved by introducing a stress gradient within
the mirror layers by a gradual change of temperature
and/or deposition voltage. Alternative methods for
introducing the desired stress gradient within the
mirror layers include the use of a secondary ion source
to selectively modify the stress within each layer of
the mirror by varying the current or voltage. In one
example, a silicon nitride layer of 0.5 micron
thickness, with 100 MPa of tensile stress, was
deposited by PECVD, and the top mirror was deposited at
100°C using ion-beam sputtering at 700V. The resulting
mirror curvature of approximately 1 mm was achieved
following removal of the sacrificial layer.
Furthermore, varying the temperature of the substrate
during the mirror deposition from room temperature to
120°C resulted in a further stress gradient in the
mirror layers, decreasing the mirror curvature to
0.75 mm.

       Akin to the confocal-cavity tunable filter
(Fig. 1), the innovative micro-cavity design using the
confocal resonator scheme also provides a stable

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fundamental spatial mode in a MEM tunable VCSEL. More

particularly, in the case of tunable VCSEL's, the gain

medium resides inside the Fabry-Perot cavity defined by

a set of planar DBR's and a set of movable curved

DBR's, as shown in Fig. 2. Excitation of the gain

medium by the fundamental mode leads to laser emission

of a single, circular spatial mode. As a result,

lateral optical mode confinement arises naturally,

without having to form a lateral waveguide. This

results in highly efficient VCSEL's.

The confocal cavity scheme is equally applicable

to a fixed wavelength VCSEL, as shown in Fig. 5. As

explained previously, the fundamental spatial mode in

the fixed wavelength VCSEL provides a stable lateral

optical confinement, and leads to a single mode laser

emission.

Competing Technologies

Currently, there are fixed-wavelength VCSEL's

commercially available below 1.0 μm.

There are no tunable VCSEL's or MEM tunable

Fabry-Perot filters commercially available at this

time.

The only commercially available tunable filters
rely on piezoelectric drivers with a complex feedback
system (Queensgate Instruments, England), or on the use
of bi-refringent materials sandwiched between
cross-polarizers (Cambridge Research Instruments,
Massachusetts, using liquid crystals).

Piezoelectric tunable filters have a resolution of
about 0.1 nm, with a 50 nm tuning range, but they also
require high voltage for operation.

Liquid crystal-based filters can exhibit better
resolution, but at the expense of low efficiency, e.g.,
as low as 99.0%.

The fabrication of the two aforementioned systems
is labor-intensive, and thus costly. For example, the
top-of-the-line model offered by Queensgate Instruments
costs more than $10,000. Such high cost, combined with
the bulkiness of these systems, make them unrealistic
for most applications. Specifically, in applications
such as future communications networks that will
deliver voice, video, data and upstream communications
to consumers, all through a single optical fiber cable,

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very low cost, compact filters and laser sources are
needed. It is believed that the feasibility of
harnessing optical fiber cable bandwidths on a broad
scale will hinge upon the availability of compact, low
cost devices such as the devices of the present
invention.

There has been some past effort towards realizing
this goal. This effort has been confined to a small
research community, and has resulted in reports of
tunable LED's, VCSEL's and MEM tunable Fabry-Perot
filters.

For example, Larson et al. have published results
on (1) a GaAs-based tunable filter (see, for example,
Larson, M. C., Pezeshki, B., and Harris, J. S.,
"Vertical coupled-cavity microinterferometer on GaAs
with deformable-membrane top mirror", IEEE Photonics
Technology Letters, Vol. 7, pp. 382-384, 1995); (2) an
LED (see, for example, Larson, M. C., and Harris,
J. S., "Broadly-tunable resonant-cavity light
emission", Applied Physics Letters, Vol. 67, No. 5,
pp. 590-592, 1995); and (3) a VCSEL (see, for example,
Larson, M. C., Massengale, A. R., and Harris, J. S.,

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"Continuously tunable micromachined vertical-cavity surface emitting laser with 18 nm wavelength range", Electronic Letters, Vol. 32, No. 19, pp. 330-332, 1996).

These results indicate that Larson et al. used GaAs/AlAs for bottom DBR's, and a gold-coated silicon-nitride membrane as the top mirror. In all of the foregoing Larson et al. devices, the top mirror release is accomplished by selectively wet-etching an underlying sacrificial layer of GaAlAs with hydrochloric acid. Since this technique provides no controlled way of undercutting, the length of the support structure for the top mirror is not well defined from device to device. Furthermore, since the top mirror in Larson et al. has lower bandwidth and reflectivity than the dielectric DBR's of the present invention, the tuning range of the devices of Larson et al. is limited, and their spectral linewidth is broader than that provided by the present invention.

Similarly, Tran et al. have shown (1) a tunable Fabry-Perot filter (see, for example, Tran, A. T. T. T., Lo, Y. H., Zhu, Z. H., Haronian, D., and Mozdy, E.,

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"Surface Micromachined Fabry-Perot Tunable Filter",

IEEE Photonics Technology Letters, Vol. 8, No. 3,

pp. 393-395, 1996); and (2) an LED (see, for example,

Christenson, G. L., Tran, A. T. T., Zhu, Z. H., Lo,

Y. H., Hong, M., Mannaerts, J. P., and Bhat, R.,

"Long-Wavelength Resonant Vertical-Cavity

LED/Photodetector with a 75-nm Tuning Range", IEEE

Photonics Technology Letters, Vol. 9, No. 6,

pp. 725-727, 1997); the aforementioned filter and LED

using polyimide as the sacrificial layer. This method

suffers from the same lack of control over precise

length fabrication. In addition, polyimide is not a

stable material for making a robust device, because

aging tends to degrade the stability of the cavity's

length.

A tunable filter (see, for example, Vail, E. C.,

Wu, M. S., Li G. S., Eng, L. and Chang-Hasnain, C. J.,

"GaAs micromachined widely tunable Fabry-Perot

filters", Electronic Letters, Vol. 31, pp. 228-229,

1995) and a VCSEL (see, for example, Vail, E. C., Li,

G. S., Yuen, W. and Chang-Hasnain, C. J., "High

performance micromechanical tunable vertical-cavity

surface-emitting lasers", Electronic Letters, Vol. 32, No. 20, pp. 1888-1889, 1996) also have been reported by Vail et al. The Vail et al. devices use GaAs/AlAs for the top and bottom DBR's, with a GaAs sacrificial layer for top DBR release. Although Vail et al. use a dry-etching technique to selectively remove the sacrificial GaAs layer, precise control of the top mirror length is still not feasible.

The present invention is distinct from the aforementioned devices in the following aspects, among others:

1.   the present invention provides a precise method for defining the lateral dimensions of the top mirror support and the cavity length by deposited supporting posts;

2.   the present invention provides an optimized control of the VCSEL gain properties by control of the strain in the deposited DBR; and

3.   the confocal design of the VCSEL structure allows single spatial modes, lower threshold and efficient coupling into a single mode fiber.

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Brief Description Of The Drawings

The description of the present invention is intended to be considered in conjunction with the drawings, wherein like elements are referred to by like reference numerals throughout, and further wherein:

Fig. 1 is a side elevational view, in cross-section, schematically and diagrammatically illustrating a microelectromechanical tunable filter having a confocal cavity;

Fig. 2 is a side elevational view, in cross-section, schematically and diagrammatically illustrating a tunable vertical cavity surface emitting laser having a confocal cavity;

Fig. 3 (i.e., Figs. 3A-3F) comprises a series of side elevational, diagrammatic, cross-sectional views schematically illustrating the fabrication procedure for making a microelectromechanical tunable filter;

Fig. 4 (i.e., Figs. 4A-4G) comprises a series of side elevational, diagrammatic, cross-sectional views schematically illustrating the fabrication procedure for making a microelectromechanical, tunable, vertical cavity surface emitting laser;

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Fig. 5 is a side elevational view, in cross-section, schematically and diagrammatically illustrating a fixed-wavelength vertical cavity surface emitting laser having a confocal cavity;

Figs. 6A-6C show top elevational diagrammatic views of three different forms of the tunable filter/VCSEL device, with Fig. 6A showing a membrane type structure, Fig. 6B showing a four tether device structure, and Fig. 6C showing a three tether device structure; and

Fig. 7 is a schematic diagram illustrating compressive strain induced in a multiple quantum well structure by strained dielectric distributed Bragg reflectors.

Further Aspects Of The Invention

A MEM tunable filter 2, and a MEM tunable VCSEL 4, are shown in Figs. 3 and 4, respectively.

More particularly, and looking now at Fig. 4, tunable VCSEL 4 includes a gain medium 6, usually comprising multiple quantum wells, located in a mechanically tunable high-Q Fabry-Perot cavity 8 formed

by a pair of spaced-apart DBR's 10 and 12,

respectively. In the present invention, one of the

DBR's 12 can be translated towards the other of the

DBR's 10 by an applied electrostatic field. This

changes the Fabry-Perot cavity length, and provides

tuning in the emission wavelength. The VCSEL can be

photo-pumped, or charge-injection may be accomplished

by intra-cavity electrical interconnections.

Further, the same basic structure, without the

gain medium, functions as a tunable filter (see

Fig. 3).

If desired, the top DBR 12 can be formed with a

curved configuration, so as to form a confocal filter

(Fig. 1) or confocal VCSEL (see Fig. 2).

Quantum wells provide the necessary gain during

stimulated emission in semiconductor lasers. In the

case of a VCSEL, the resonant optical mode inside the

micro-cavity interacts with an extremely small volume

of this gain medium. As a result, it is important to

provide maximum gain per quantum well over the

interaction volume. The best method for accomplishing

this is to grow the quantum wells under compressive

strain. Compressive strain in the quantum wells leads to anisotropy in the band structure, and to splitting of the degeneracy of the in-plane heavy-hole and light-hole bands, resulting in heavy-hole band shifting of several tens of meV (for 1% compressive strain) above the light-hole band. While the anisotropy leads to a reduction in the in-plane heavy-hole effective mass, which reduces the density of states available for transition near the zone center, the splitting of the degeneracy leads to a preferential population inversion between the conduction band and the desired heavy-hole band. Due to these two effects, the threshold current density decreases, temperature sensitivity is improved, and differential efficiency increases. Compressively strained multiple quantum wells are especially desirable at about 1300 nm and about 1500 nm, since Auger recombination and inter-valence band absorption contribute to intrinsic loss at these long wavelengths. Therefore, the importance of maximizing gain in VCSEL's cannot be over-emphasized.

Strained multiple quantum wells are difficult to grow, and are expensive compared to unstrained quantum

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wells.

In the present invention, a method is provided for introducing a desired strain in the unstrained quantum wells of any semiconductor material after the crystal has been grown. The process requires depositing dielectric films with a controlled amount of strain. In the case of VCSEL's, it has been found preferable to deposit one of the DBR stacks with a judiciously chosen strain.

For example, and looking now at Fig. 7, in order to induce compressive strain in the quantum wells, DBR stacks 10, with tensile strain, will be deposited on top of a MQW structure 6 (for example, a InGaAsP/InGaAs MQW), and subsequently flip-chip bonded to a temporary host substrate 20 such as silicon. Thereafter, the temporary host substrate 20 will be selectively removed using an epitaxial lift-off process, and the second set of DBR's will be deposited.

The amount of strain introduced into the MQW by the foregoing process may be approximated by the following equation:

$$\frac{\Delta a}{a} = -\frac{2Pl_2}{c_{11}l_1}$$

where P is the compressive stress in one of the DBR layers; c_{11} is the average coefficient of stiffness (Young's modulus) of the MQW layers; l_2 is the thickness of the MQW layers; and l_1 is the thickness of the dielectric DBR's. From this equation, it is evident that several Mega Pascals of tensile strain in the DBR's will induce roughly 1% compressive strain in the MQW that are initially lattice-matched. Controlled strain in the DBR's can be introduced by controlling the energy of the ion-beam during deposition of the DBR's, as discussed above. Typically, a few Kilo Pascal to a few Giga Pascal of stress (tensile or compressive) can be introduced in DBR pairs of Si/Al_2O_3, Si/SiO_2, Si/MgO or TiO_2/SiO_2 in this manner.

Device Fabrication

A schematic top view of three embodiments of the tunable VCSEL or filter structure is depicted in Figs. 6A-6C.

In Figs. 3 and 4, schematic cross-sectional views

of the fabrication steps used in making

microelectromechanical, tunable filters and VCSEL's are

shown, respectively. Although the two structures

(i.e., the tunable filters and VSCEL's) resemble each

other in form, there are subtle differences in the

fabrication steps utilized in making the two different

devices. The fabrication steps for each of these

devices are discussed in detail below.

MEM Tunable VCSEL/Filter Fabrication Procedure

1.   When fabricating a tunable VCSEL, DBR's 10

are deposited on top of the MQW structure 6. The MQW

structure 6, with the DBR's 10 deposited thereon, is

applied to a suitable temporary substrate 20, such as

silicon, GaAs or sapphire. This is accomplished by a

method such as flip-chip bonding, fusion bonding or

Van der Waals bonding (see Fig. 4A). On the other

hand, when fabricating a tunable filter, the DBR's 10

are deposited directly onto a host substrate of choice

24 (Fig. 3A).

2.   When fabricating a tunable VCSEL, the

structure of Fig. 4A is mounted to a host substrate of

choice 24 (Fig. 4B). Next, the temporary substrate 20, upon which the MQW structure 6 resides, is selectively removed by an etch-back technique (Fig. 4B). In this method, a highly selective etchant is used to etch the temporary substrate 20, and etching is terminated at a strategically located etch-stop layer 26. It has been found that a one-to-one mixture of concentrated hydrochloric acid and hypochloric acid removes InP preferentially over InGaAs. In the case of a GaAs substrate, a citric acid and hydrogen peroxide mixture can be used for selective removal of the temporary substrate 20 over AlAs. Another approach, which has been found to be useful with GaAs substrates, is to grow a thin layer of AlAs between the temporary substrate 20 and the MQW structure 6 deposited thereon. The AlAs may then be selectively etched. This allows the MQW structure 6 to be lifted away from the GaAs substrate.

3.   At this stage, one of the tuning electrodes, 28, is deposited on top of the DBR layer 10 in the case of a tunable filter 2 (Fig. 3B), and on top of the MQW structure 6 in the case of tunable VCSEL 4 (Fig. 4C).

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If appropriate, an isolation layer 29 (i.e., an
electrically insulating layer) may then be deposited
atop some or all of the electrodes 28. See, for
example, Fig. 4C, where an isolation layer 29 is shown
(in phantom) atop electrodes 28.

    4.   After the DBR layer 10 (in the case of a
filter), or the MQW structure 6 and DBR layer 10 (in
the case of a VCSEL), has been deposited on the
substrate 24, a calibrated thickness 30 of polyimide,
or aluminum, or some other sacrificial material, is
deposited on top of the MQW structure 6 in the case of
tunable VCSEL (Fig. 4D), and on top of the DBR layer 10
in the case of a tunable filter (Fig. 3C). The
polyimide or aluminum structure 30 will act as a
sacrificial layer later in the method as described in
detail below. It should be appreciated that it is very
important to accurately control the thickness and
lateral dimensions of the polyimide or aluminum
structure 30. This is because the thickness of this
deposit will determine the ultimate length of the air
cavity 8 in the tunable Fabry-Perot device and, hence,
the unbiased resonant wavelength of the device. The

lateral dimension of the polyimide or aluminum deposit
30, on the other hand, determines the voltage response
of the device and the resonance frequency.

5.   Thereafter, an etch-mask is used to pattern
the polyimide or aluminum deposit 30 so as to leave a
circular disk-shaped deposit defining an outwardly
slanted edge 32 on its etched perimeter (Figs. 3C and
4D). The size and shape of the etched deposit 30 is
carefully designed and controlled because its outer
surface will determine the length of the top mirror
support. Specifically, the disk of polyimide or
aluminum acts like a "micro-die" which precisely
controls the lateral dimensions and shape of the
tunable VCSEL or filter. This precise control of the
lateral dimensions of the tunable VCSEL or filter is
unparalleled by any existing techniques employed in
existing MEM tunable VCSEL or filter fabrication. As
alluded to above, later in the process, the polyimide
or aluminum layer 30 will be selectively removed using
a suitable dry-etching technique.

6.   In the case wherein a Si_3N_4 membrane is used
for top mirror support, a thin layer 36 (Figs. 3D and

4E) of metal is first deposited on the exposed top
surface of the polyimide or aluminum deposit to form
the top tuning electrode.

7.   Thereafter, either a thin layer of silicon
nitride or a thin layer of another metal other than
aluminum, e.g., titanium-tungsten (TiW), generally
shown at 37, is deposited over the entire structure,
i.e., over the polyimide or aluminum sacrificial layer
30 and the remaining structure (Figs. 3D and 4E). In
the case where layer 37 is not transparent, the center
portion is removed (see Figs. 3D and 3E, and Fig. 4E).

8.   A thick layer 38 of metal (such as Al or TiW)
or hard dielectrics (such as silicon nitride) forming a
rim (in case of a membrane type device such as is shown
in Fig. 6A) or patches of support forming arms (in the
case of a tether device such as is shown in
Figs. 6B or 6C) is then selectively deposited on the
periphery of the device where the device membrane or
tethers meet the bottom DBR. The width of annulus or
support patches 38 is selected such that a thick metal
rim extends from the top of the bottom DBR 10, over the
sloped edge 32 of the sacrificial layer 30 of polyimide

or aluminum, and onto the top of the sacrificial disk
30, as indicated in Figs. 3E and 4F. This is an
important innovation because the thick metal structure
38 provides robust support to the thin membrane 37 of
silicon nitride or TiW after the underlying sacrificial
layer 30 of polyimide or aluminum has been removed.

9.   Using an etch-mask, radially emanating
openings 40 (Fig. 6A) then are formed by etching
through the transparent metal and silicon nitride or
the thin (TiW) film, 37, down to the underlying
sacrificial disk 30. These openings provide gateways
for the etchants to selectively remove the underlying
sacrificial disk 30.

10.   A circular top DBR stack 12, extending tens
of micrometer in diameter, is then selectively
deposited only at the center 42 (Figs. 3E, 4G and
6A-6C) of the silicon nitride/metal membrane or TiW
film 37. This selective deposition provides an
extremely good quality DBR, and avoids having to etch
the top DBR, which can be a difficult and costly
effort. To the extent that top DBR stack 12 is to
assume a curved configuration in the completed device

(e.g., as shown in Figs. 1 and 2), an appropriate
magnitude and type of strain is introduced into top DBR
stack 12 during deposition of the top DBR stack, in the
manner discussed above.

11. Finally, an oxygen plasma is used to
selectively remove the polyimide layer 30 (Figs. 3F and
4G). This releases the silicon nitride/metal membrane
37 along with the top DBR 12. To the extent that top
DBR stack 12 is formed with an appropriate magnitude
and type of strain to result in the formation of a
curved DBR stack, the release of silicon nitride/metal
membrane 37 permits the top DBR stack 12 to assume its
desired curved configuration. CF_4 plasma is used in
the case of selective removal of an aluminum
sacrificial layer 30. Since wet chemistry is not
involved, there is no risk of the released silicon
nitride/metal membrane or TiW film, 37, collapsing due
to surface tension.

This completes the fabrication of a MEM tunable
filter/VCSEL in which lasing can be accomplished by
photo-pumping with a separate pump laser having a
wavelength that is highly absorptive within the gain

spectrum of the MQWs being used. The techniques

discussed in the present invention to achieve

wavelength tuning can be easily adapted to a

current-injected MEM tunable VCSEL as well. In this

situation, intra-cavity electrical interconnections

have to be made to the p-i-n junction in the MQW

structure after the first mirror deposition step, which

was explained in step 1 of the tunable VCSEL

fabrication procedure.

It will be understood that the foregoing detailed

description of preferred embodiments of the invention

has been presented by way of illustration, and not

limitation. Various modifications, variations,

changes, adaptations and the like will occur to those

skilled in the art in view of the foregoing

specification. Accordingly, the present invention

should be understood as being limited only by the terms

of the claims.

What Is Claimed Is:

1.   A method for introducing a pre-selected
amount, and type, of strain into the quantum wells of a
pre-grown crystalline semiconductor material, said
method comprising the steps of:

providing a member formed of said crystalline
semiconductor material, said member having an upper
surface and defining multiple quantum wells; and

depositing at least one thin film layer on said
upper surface of said member, said at least one thin
film layer containing a pre-selected amount, and type,
of strain, said type of strain in said at least one
thin film layer being the opposite type to that desired
to be introduced into said member.

2.   A method according to claim 1 wherein said at
least one thin film layer comprises a dielectric
material.

3.   A method according to claim 2 wherein said
dielectric material is selected from the group

consisting of silicon nitride, silicon dioxide and aluminum oxide.

4.   A method according to claim 1 wherein said at least one thin film layer comprises a non-dielectric material.

5.   A method according to claim 4 wherein said non-dielectric material is selected from the group consisting of chromium, nickel chromium, titanium gold, titanium platinum, titanium dioxide and magnesium oxide.

6.   A method according to claim 1 wherein said step of depositing said at least one thin film layer is achieved by means of ion-beam assisted electron-beam evaporation.

7.   A method according to claim 6 wherein the amount, and type, of strain in said at least one thin film layer is determined by controlling the ion-beam voltage and current of the "sputtering" or "assisting"

ions.

        8.   A method according to claim 6 wherein the

amount, and type, of strain in said at least one thin

film layer is determined by controlling the temperature

of said member.

        9.   A method according to claim 1 wherein said

step of depositing said at least one thin film layer is

achieved by means of ion-beam sputtering.

        10.   A method according to claim 9 wherein the

amount, and type, of strain in said at least one thin

film layer is determined by controlling the ion-beam

voltage and current.

        11.   A method according to claim 9 wherein the

amount, and type, of strain in said at least one thin

film layer is determined by controlling the temperature

of said member.

        12.   A method according to claim 1 wherein said at

least one thin film layer comprises one of the group consisting of Si; Al$_2$O$_3$; SiO$_2$; TiO$_2$; MgO; Ta$_2$O$_5$; zirconium oxide; or any combination thereof.

13. A method according to claim 1 wherein said quantum wells are unstrained prior to the application of said at least one thin film layer.

14. A method according to claim 1 wherein said quantum wells are under tensile strain prior to the application of said at least one thin film layer.

15. A method according to claim 1 wherein said quantum wells are under compressive strain prior to the application of said at least one thin film layer.

16. A method according to claim 1 wherein the amount, and type, of strain in said at least one thin film layer is selected so as to maximize the compressive strain in said quantum wells without damage to said member.

17.   A method according to claim 1 wherein the amount, and type, of strain in said at least one thin film layer is selected so as to maximize the tensile strain in said quantum wells without damage to said member.

18.   A method according to claim 1 wherein said material is incorporated into an edge-emitting laser.

19.   A method according to claim 18 wherein the amount, and type, of strain is selected so as to optimize the optical gain coefficient of said laser.

20.   A method according to claim 1 wherein said material is incorporated into a vertical cavity surface emitting laser.

21.   A method according to claim 20 wherein the amount, and type, of strain is selected so as to optimize the optical gain coefficient of said laser.

22.   A microelectromechanically tunable vertical

cavity surface emitting laser, said laser comprising:

(a)   a substrate having an upper surface;

(b)   a first mirror having a first upper surface located on the upper surface of said substrate;

(c)   a layer of gain material having a second upper surface and defining multiple quantum wells, said layer of gain material being located on said first upper surface;

(d)   a first electrode deposited on said second upper surface;

(e)   a membrane having an upper surface and a lower surface, at least part of said membrane carrying a second electrode on its lower surface in spaced relation to said first electrode, said membrane defining the length and lateral dimensions of an air cavity located between said first and second electrodes;

(f)   a thick support structure, said support structure connecting said second upper surface to the periphery of said at least a part of said membrane carrying said second electrode, said support structure being adapted to stabilize said membrane; and

(g) a second mirror located centrally of said at least a part of said membrane carrying said second electrode, said second mirror being disposed on said upper surface of said membrane,

wherein said second mirror is translatable relative to said first mirror in response to an electric field applied between said electrodes.

23. A laser according to claim 22 wherein said substrate comprises a semiconductor material.

24. A laser according to claim 22 wherein said multiple quantum wells are compressively stressed.

25. A laser according to claim 22 wherein said mirrors comprise distributed Bragg reflectors.

26. A laser according to claim 25 wherein said distributed Bragg reflectors comprise alternating layers of quarter-wavelength thick deposited dielectric films.

27.   A laser according to claim 26 wherein said dielectric films are fabricated from the group consisting of Si; Al_2O_3; SiO_2; TiO_2; MgO; Ta_2O_5; zirconium oxide; or any combination thereof.

28.   A laser according to claim 22 wherein said membrane comprises a plurality of openings therethrough, between said second mirror and said support structure.

29.   A laser according to claim 28 wherein said openings comprise radial slits.

30.   A laser according to claim 28 wherein said openings comprise holes.

31.   A laser according to claim 28 wherein said openings comprise a spiral slit.

32.   A laser according to claim 22 wherein said support structure comprises an annulus formed from a material selected from the group consisting of silicon

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nitride and titanium tungsten.

33.   A laser according to claim 22 wherein said
membrane is fabricated from the group consisting of
Si_3N_4 and TiW.

34.   A laser according to claim 22 wherein said
first mirror is planar and said second mirror is
curved, so as to form, between said mirrors, a confocal
stable resonator.

35.   A laser according to claim 34 wherein said
confocal stable resonator has a well-defined
near-Gaussian mode structure.

36.   A laser according to claim 34 wherein said
second mirror has a radius of curvature, said radius of
curvature being optimized such that said mode size of
said cavity matches the size of the core of an optical
fiber.

37.   A microelectromechanically tunable

Fabry-Perot filter, said filter comprising:

(a)   a substrate having an upper surface;

(b)   a first mirror having a first upper surface located on the upper surface of said substrate;

(c)   a first electrode deposited on said second upper surface;

(d)   a membrane having an upper surface and a lower surface, at least part of said membrane carrying a second electrode on its lower surface in spaced relation to said first electrode, said membrane defining the length and lateral dimensions of an air cavity located between said first and second electrodes;

(e)   a thick support structure, said support structure connecting said second upper surface to the periphery of said at least a part of said membrane carrying said second electrode, said support structure being adapted to stabilize said membrane; and

(f)   a second mirror located centrally of said at least a part of said membrane carrying said second electrode, said second mirror being disposed on said upper surface of said membrane,

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wherein said second mirror is translatable relative to said first mirror in response to an electric field applied between said electrodes.

38.   A Fabry-Perot filter according to claim 37 wherein said substrate comprises a semiconductor material.

39.   A Fabry-Perot filter according to claim 37 wherein said mirrors comprise distributed Bragg reflectors.

40.   A Fabry-Perot filter according to claim 39 wherein said distributed Bragg reflectors comprise alternating layers of quarter-wavelength thick deposited dielectric films.

41.   A Fabry-Perot filter according to claim 40 wherein said dielectric films are fabricated from the group consisting of Si; Al_2O_3; SiO_2; TiO_2; MgO; Ta_2O_5; zironium oxide; or any combination thereof.

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42. A Fabry-Perot filter according to claim 37 wherein said membrane comprises a plurality of openings therethrough, between said second mirror and said support structure.

43. A Fabry-Perot filter according to claim 42 wherein said openings comprise radial slits.

44. A Fabry-Perot filter according to claim 42 wherein said openings comprise holes.

45. A Fabry-Perot filter according to claim 42 wherein said openings comprise a spiral slit.

46. A Fabry-Perot filter according to claim 37 wherein said support structure comprises an annulus formed from a material selected from the group consisting of silicon nitride and titanium tungsten.

47. A Fabry-Perot filter according to claim 37 wherein said membrane is fabricated from the group consisting of Si_3N_4 and TiW.

48.   A Fabry-Perot filter according to claim 37 wherein said first mirror is planar and said second mirror is curved, so as to form, between said mirrors, a confocal stable resonator.

49.   A Fabry-Perot filter according to claim 48 wherein said confocal stable resonator has a well-defined near-Gaussian mode structure.

50.   A Fabry-Perot filter according to claim 48 wherein said second mirror has a radius of curvature, said radius of curvature being optimized such that said mode size of said cavity matches the size of the core of an optical fiber.

51.   A method for making a microelectromechanically tunable, vertical cavity surface emitting laser, said method comprising the steps of:

(a)   providing a member having a substrate, a first mirror disposed on said substrate, and a layer of

gain material disposed on said first mirror;

(b) depositing a first electrode onto said gain material;

(c) depositing a calibrated thickness of a sacrificial material on top of said gain material and said first electrode;

(d) etch-masking said sacrificial material so as to create a central structure having an inwardly sloped perimeter edge on said gain material/first electrode structure;

(e) depositing a second electrode on said central structure;

(f) depositing a thin layer of a second material on top of the gain material/central structure/second electrode structure;

(g) depositing a thick annulus of support material onto said layer of second material such that said annulus covers the sloped perimeter edge of said support structure and extends inwardly thereof, adjacent to and parallel to the top surface of said central structure, and outwardly thereof, adjacent to and parallel to the upper surface of said gain

material;

(h) etch-masking openings through said layer of
second material adjacent to the top of said central
structure, between a substantially circular center
portion thereof and the inner edge of said annulus;

(i) selectively depositing a second mirror onto
said substantially circular center portion; and

(j) selectively removing said central structure
through said openings using an etching technique.

52. A method according to claim 51 wherein said
sacrificial material is selected from the group
consisting of polyimide, aluminum and photoresist.

53. A method according to claim 51 wherein said
central structure is in the form of a disk.

54. A method according to claim 51 wherein said
central structure is in the form of a polygon.

55. A method according to claim 51 wherein said
second material is selected from the group consisting

of silicon nitride and metals other than aluminum.

56.   A method according to claim 51 wherein said
support material is selected from the group consisting
of silicon nitride or a metal.

57.   A method according to claim 51 wherein said
etching technique comprises dry etching.

58.   A method according to claim 51 wherein said
etching technique comprises wet etching.

59.   A method according to claim 51 wherein said
first and second mirrors comprise distributed Bragg
reflectors.

60.   A method according to claim 51 wherein the
material of said mirrors is selected from the group
consisting of Si; Al_2O_3; SiO_2; TiO_2; MgO; Ta_2O_5;
zirconium oxide; or any combination thereof.

61.   A method according to claim 51 wherein said

thick metal annulus is formed of TiW.

62.   A method according to claim 51 wherein said
central structure is formed of polyimide and said
etching is accomplished with oxygen plasma.

63.   A method according to claim 51 wherein said
central structure comprises aluminum, and said etching
is accomplished using CF_4 plasma.

64.   A method according to claim 51 wherein said
first mirror is planar and, subsequent to step (j),
said second mirror is curved, so as to form, between
said mirrors, a confocal stable resonator.

65.   A method according to claim 64 wherein said
confocal stable resonator has a well-defined
near-Gaussian mode structure.

66.   A method according to claim 64 wherein the
curvature of said second mirror is controlled by
introducing a stress gradient within said second

mirror.

67.   A method according to claim 66 wherein said
stress gradient is created by controlled changes in
deposition temperatures or deposition voltage.

68.   A method for making a
microelectromechanically tunable Fabry-Perot filter,
said method comprising the steps of:

(a)   depositing a first mirror onto the upper
surface of a substrate;

(b)   depositing a first electrode onto said first
mirror;

(c)   depositing a calibrated thickness of a
sacrificial material on top of the substrate/first
mirror/first electrode structure;

(d)   etch-masking said sacrificial material so as
to leave a central structure having an inwardly sloped
perimeter edge on said first mirror/first electrode
structure;

(e)   depositing a second electrode on top of said
central structure;

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(f)   depositing a thin layer of a second material on top of the central structure/second electrode/substrate structure;

(g)   depositing a thick annulus of support material onto said layer of second material such that said annulus covers the sloped perimeter edge of said central structure and extends inwardly thereof, adjacent to and parallel to the top surface of said central structure, and outwardly thereof, adjacent to and parallel to the upper surface of said first mirror;

(h)   etch-masking openings through the layer of second material adjacent to the top of said central structure, between a substantially circular center portion thereof and the inner edge of said annulus;

(i) selectively depositing a second mirror onto said substantially circular center portion; and

(j)   selectively removing said central structure through said openings using an etching technique.

69.   A method according to claim 68 wherein said first mirror is planar and, subsequent to step (j), said second mirror is curved, so as to form, between

said mirrors, a confocal stable resonator.

70.   A method according to claim 68 wherein said
sacrificial material is selected from the group
consisting of polyimide, aluminum and photoresist.

71.   A method according to claim 68 wherein said
central structure is in the form of a disk.

72.   A method according to claim 68 wherein said
central structure is in the form of a polygon.

73.   A method according to claim 68 wherein said
second material is selected from a group consisting of
silicon nitride and metals other than aluminum.

74.   A method according to claim 68 wherein said
support material is selected from the group consisting
of silicon nitride or a metal.

75.   A method according to claim 68 wherein said
etching technique comprises dry etching.

76.   A method according to claim 68 wherein said
etching technique comprises wet etching.

77.   A method according to claim 68 wherein said
first and second mirrors comprise distributed Bragg
reflectors.

78.   A method according to claim 68 wherein the
material of said mirrors is selected from the group
consisting of Si; Al_2O_3; SiO_2; TiO_2; MgO; Ta_2O_5;
zirconium oxide; or any combination thereof.

79.   A method according to claim 68 wherein said
thick metal annulus is formed of TiW.

80.   A method according to claim 68 wherein said
central structure is formed of polyimide and said
etching is accomplished with oxygen plasma.

81.   A method according to claim 68 wherein said
central structure comprises aluminum, and said etching

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is accomplished using CF_4 plasma.

82.   A method according to claim 9 wherein said
step of depositing said at least one thin film layer is
achieved by means of ion-beam assisted ion-beam
sputtering.
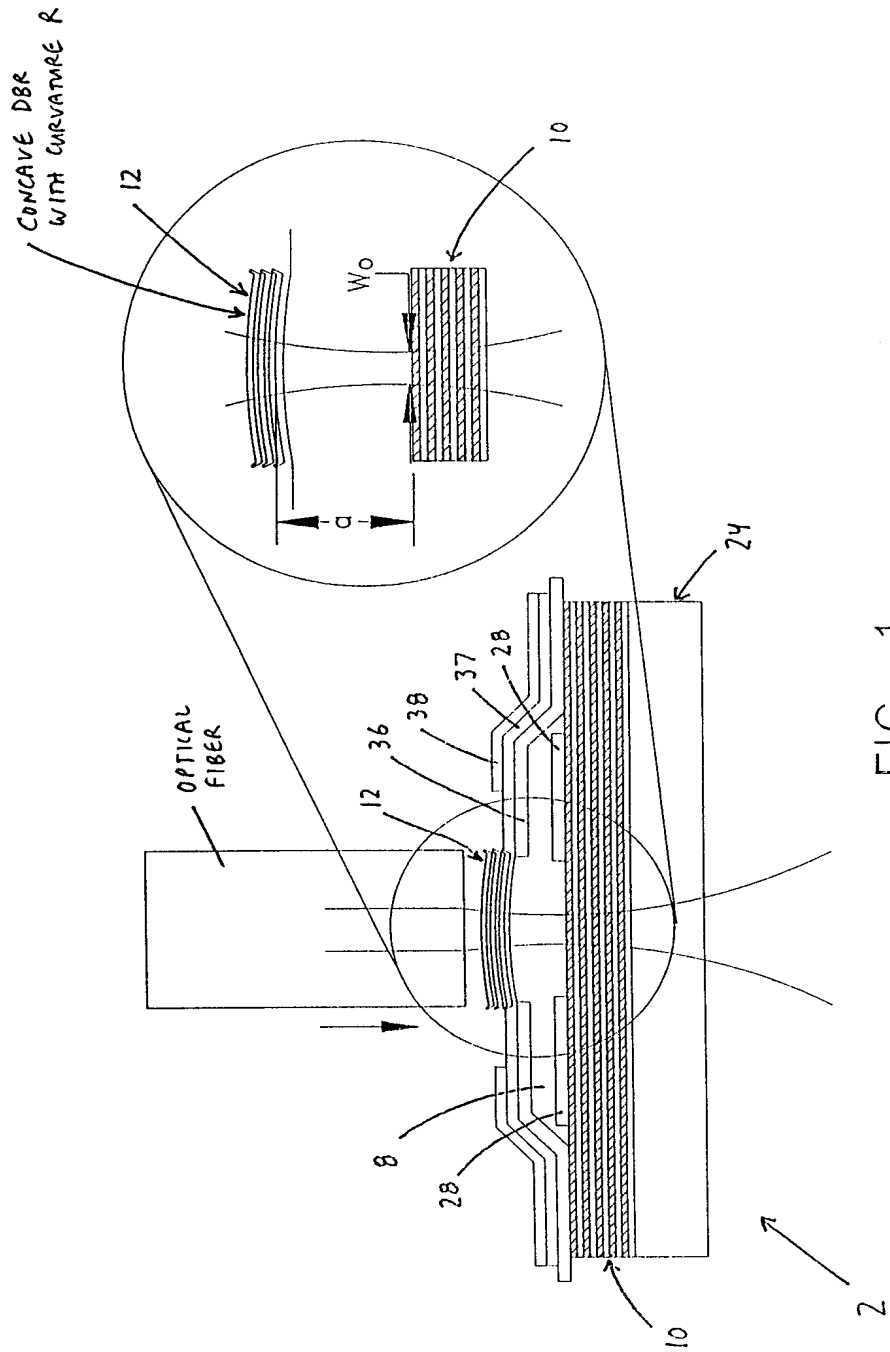
FIG. 1

MEM TUNABLE FILTER
WITH CONFOCAL CAVITY
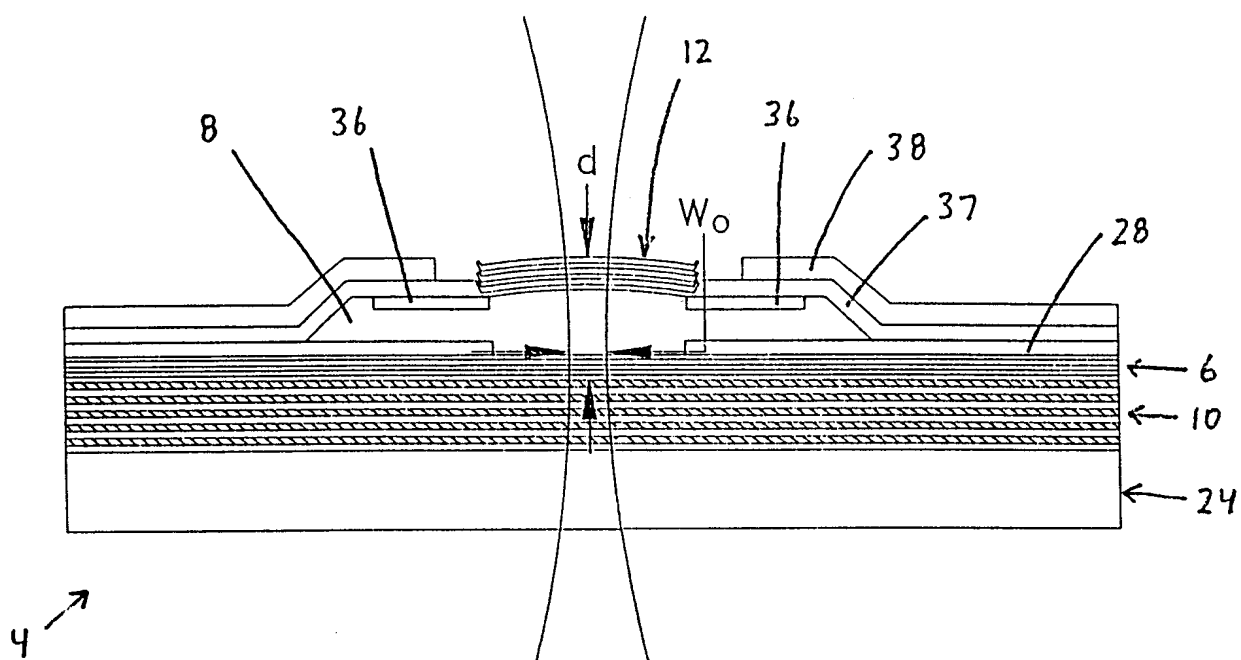
FIG. 2

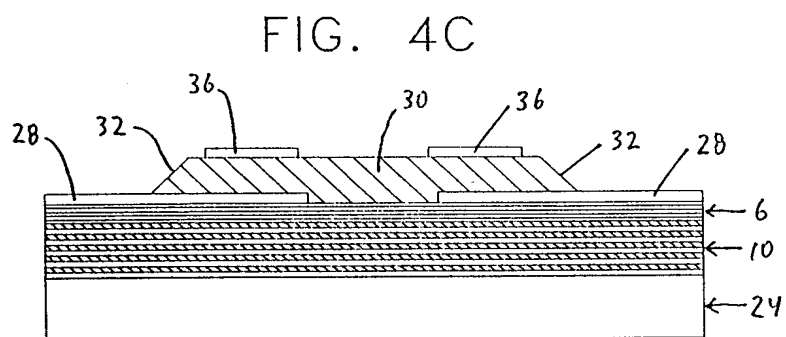TUNABLE VCSEL WITH CONFOCAL CAVITY
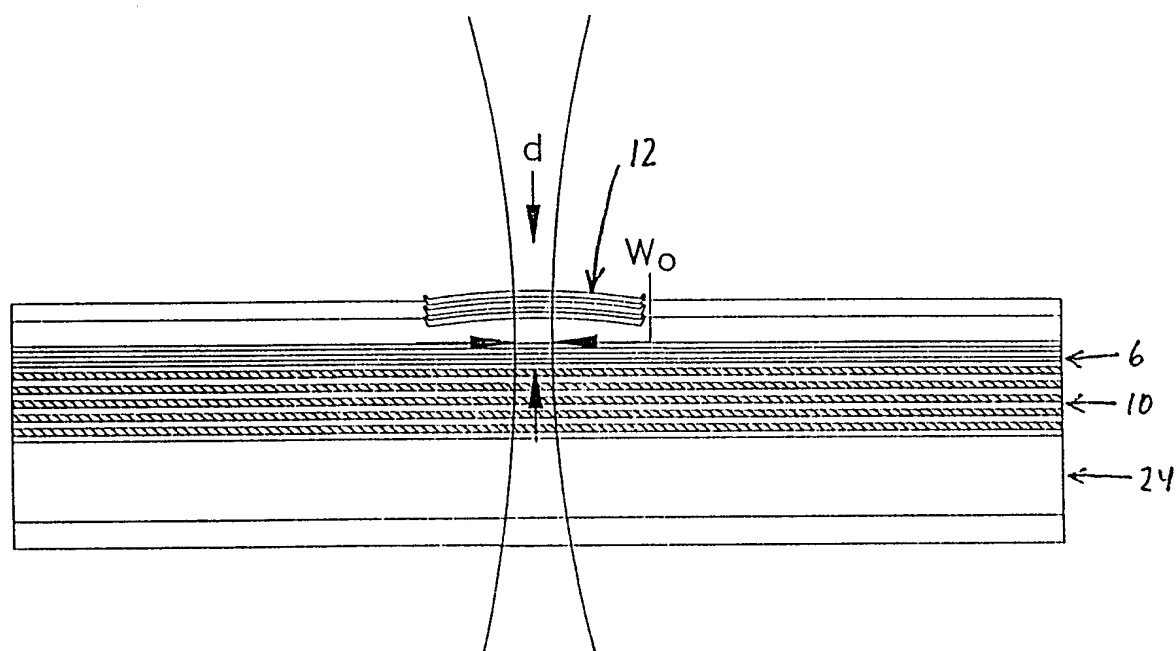
FIG. 5

FIXED WAVELENGTH VCSEL
WITH CONFOCAL CAVITY

FIG. 3 SHOWS FABRICATION PROCEDURE
        FOR MEM TUNABLE FILTER
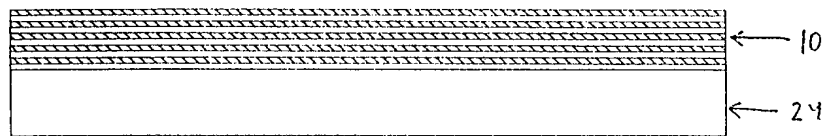
FIG. 3A
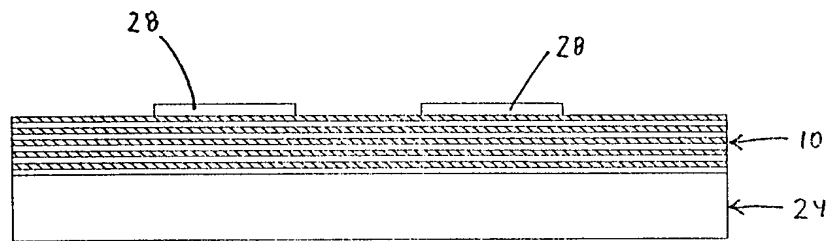
FIG. 3B
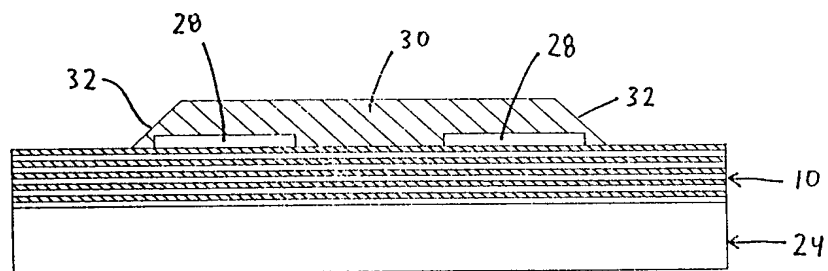
FIG. 3C
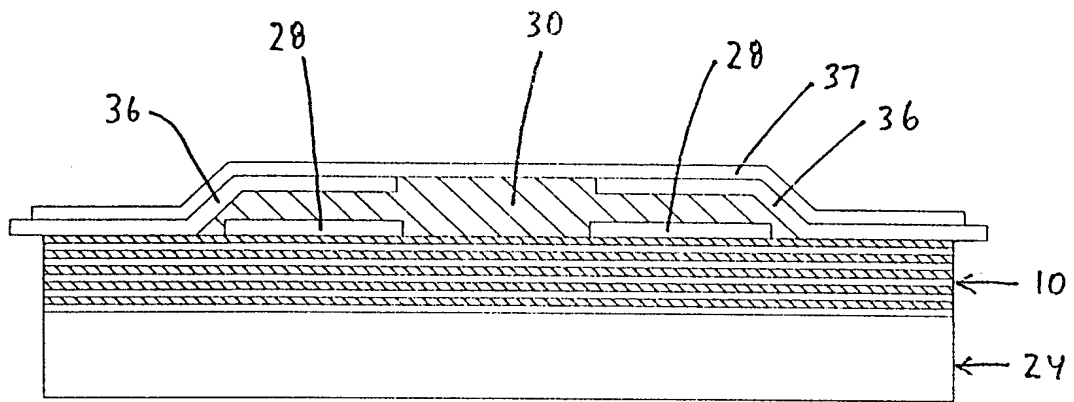
FIG. 3D
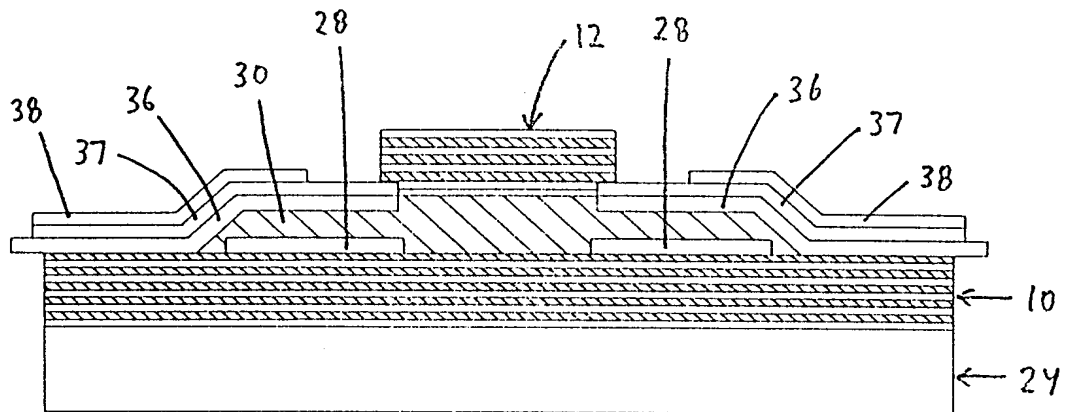
FIG. 3E
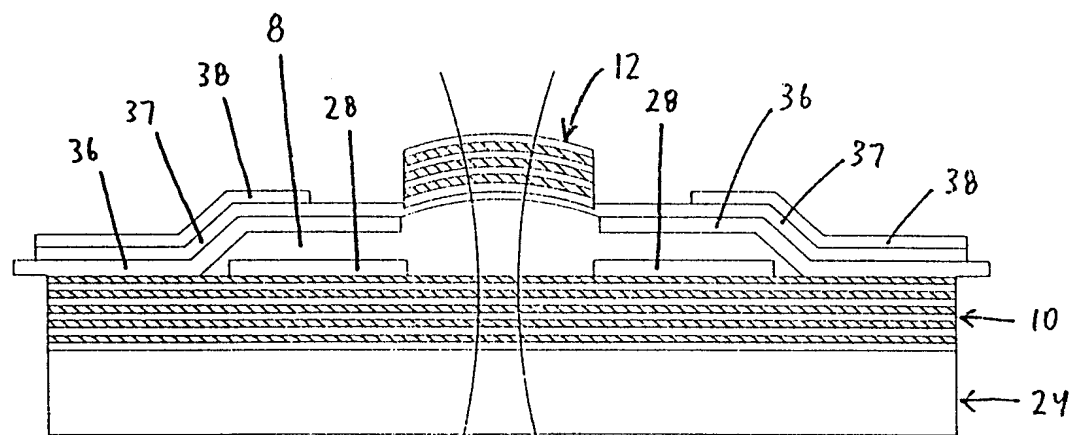
FIG. 3F

FIG. 4 SHOWS FABRICATION PROCEDURE
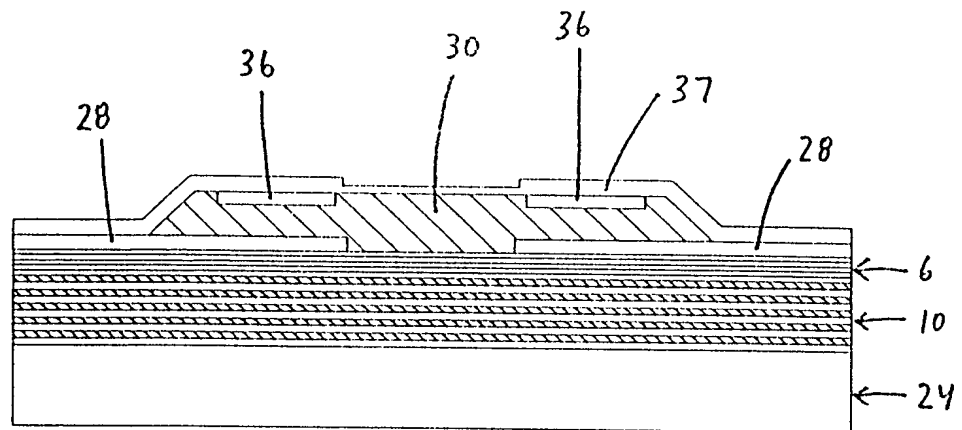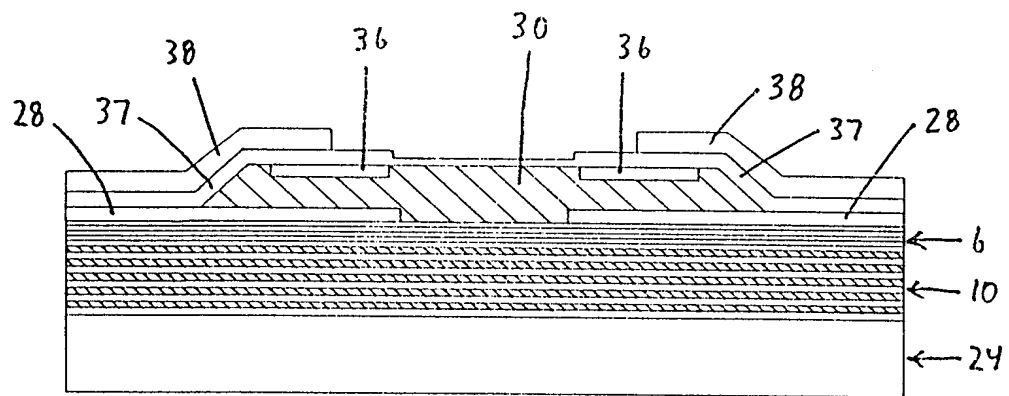FOR MEM TUNABLE VCSEL

FIG. 4A

FIG. 4B
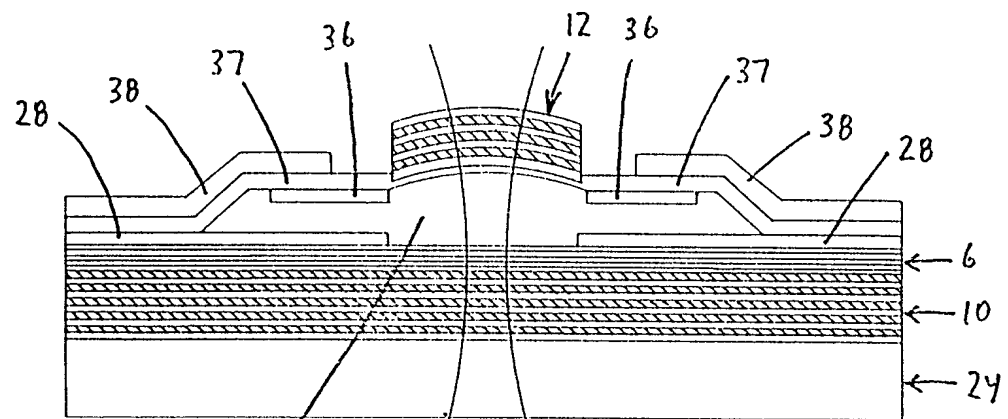

FIG. 4C

FIG. 4D
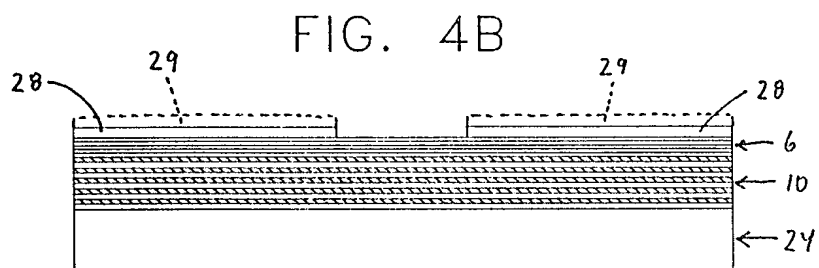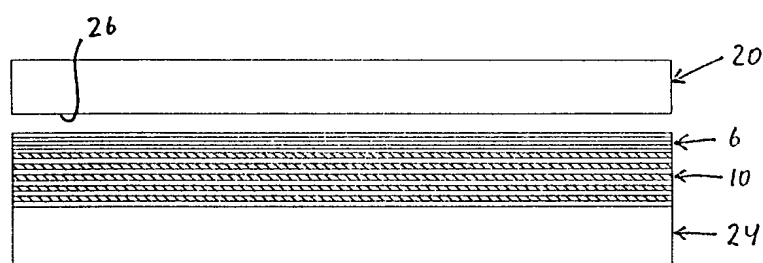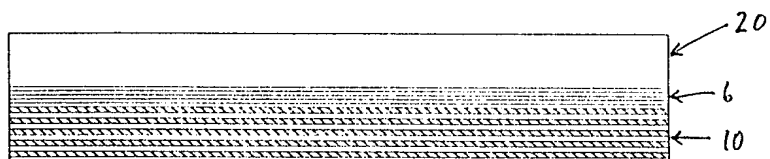
FIG. 4E

FIG. 4F

FIG. 4G

FIG. 6 SHOWS DIFFERENT FORMS
        OF TUNABLE FILTER/VCSEL DEVICES

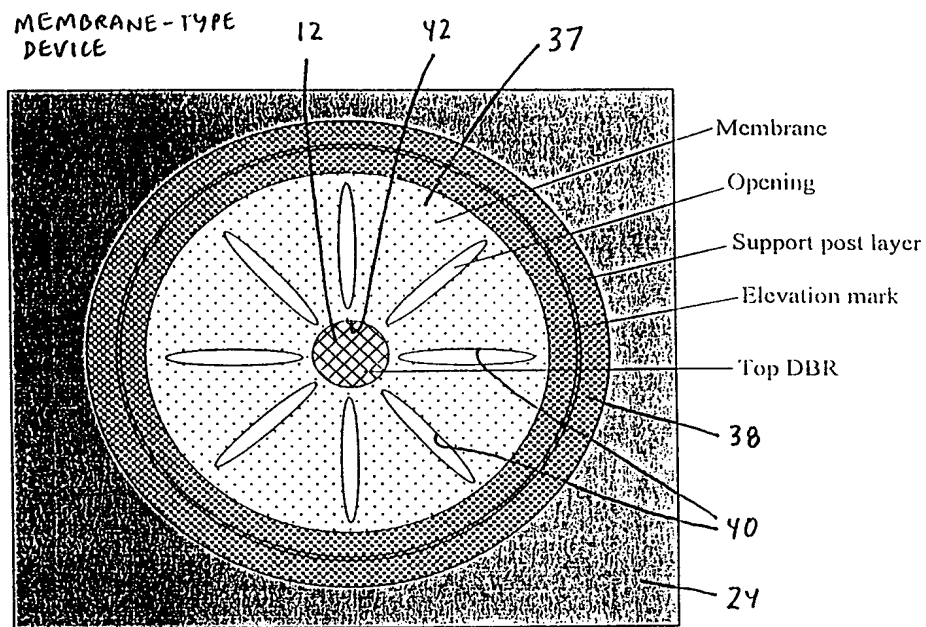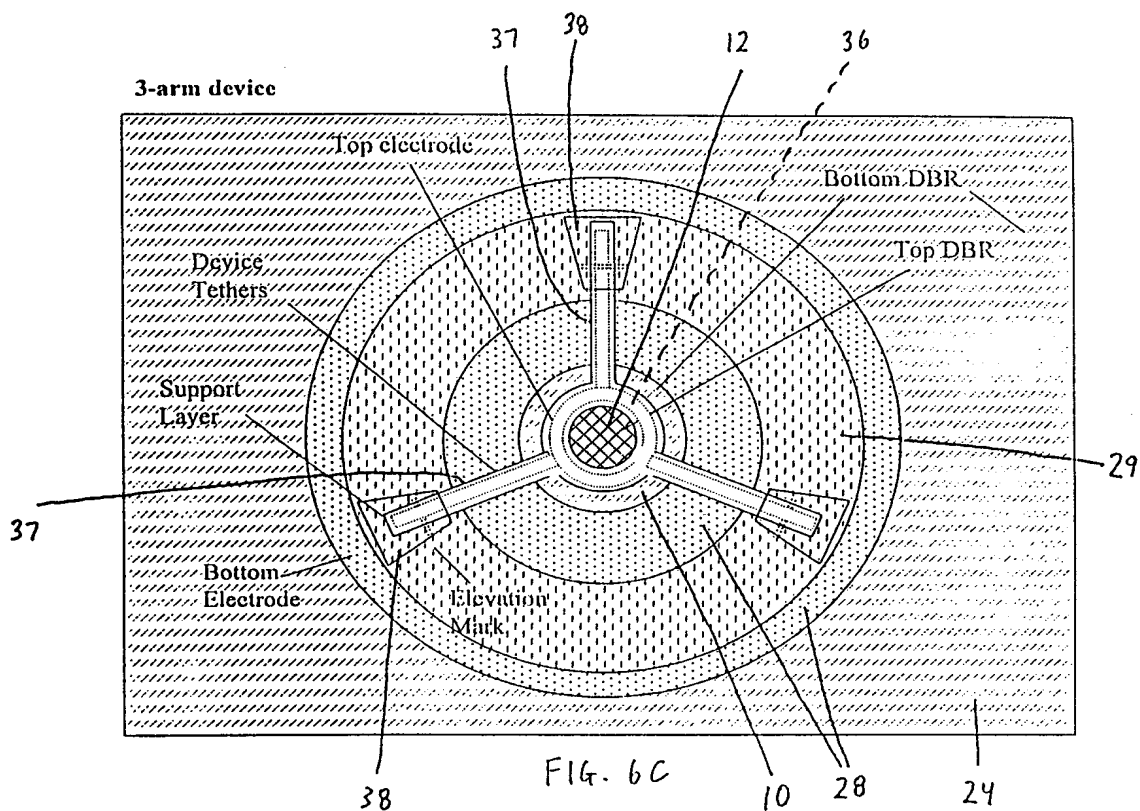MEMBRANE-TYPE
DEVICE   12   42   37

Membrane

Opening

Support post layer

Elevation mark

Top DBR

38

40

24

FIG. 6A

4-arm device   38   12   36

Top electrode

Bottom DBR

Top DBR

Device
Tethers   28

Support
Layer   38

Elevation
Mark   29

Bottom
Electrode   Isolation
                   Layer   24

10   FIG. 6B   37   37

FIG. 6C

FIG. 7